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HIGH-TEMPERATURE LIQUID METAL TRANSPORT PHYSICS OF CAPILLARY PUMPING HEAT TRANSPORT SYSTEM (CPHTS) RESEARCH (Preprint)

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Structures Division

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Interim Report

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14. ABSTRACT
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15. SUBJECT TERMS

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■ RESEARCH OBJECTIVE

The objective of research is to experimentally and theoretically study multi-scale heat and mass transport phenomena in evaporating liquid sodium thin film using a specially designed rig at the Facilities for Innovative Research in Structures Technology (FIRST) Laboratory in Building 65 at WPAFB.

■ PROPOSED TASKS

I. Experimental characterization of evaporating liquid metal (Na) thin film for its multi-scale (nano/micro/meso-scales) heat and mass transport phenomena.

II. Theoretical predictions and parametric studies of multiscale heat and mass transport physics of evaporative liquid metal thin film and bulk meniscus.

■ **SUMMARY OF ACHIEVEMENT**

1. Multi-Scale Experimental Characterization of Evaporating Sodium Capillary

Previous study[1] showed that the high temperature sodium vapor reacted with the *quartz-made* capillary surfaces and deposited condensation “fingerprints” on the capillary inner wall (see Appendix A). The capillary wall turned into highly opaque that sodium meniscus inside was no longer visible.

A number of parallel efforts have been exploited to alleviate this problem and also improve the experimental layout.

<u>1-a. Design and fabrication of a sapphire cube</u>

First, a 100% sapphire-made cube (1” x 1” x 4”) with sharp inner corners was proposed to consider based on the fact that sapphire is more inert to sodium vapor attack. The expectation has been that once the cube is filled and sealed with sodium, the evaporative meniscus rising on one of the corners can be visible under heating with minimal surface reaction.

After contacting three different sapphire fabrication companies and having substantial amount of discussions regarding the cube design, however, we have found a number of huddles to overcome to proceed with the original idea:

1. **Time** - It will take up to 4 months (probably more) for them to complete one cube.
2. **Cost** - The basic tooling and engineering will cost $15k and each cube will cost $13k.
3. **Surface finish** – The optical clarity of the inner walls may not be possible to accomplish to the level of our imaging requirements.
4. **Sharp inner corner** – This will be not only difficult for machining, if not impossible, but also causing stress fault in the sapphire structures.
5. **Residual cracks** – Vibration and shocks from the machining process may cause microscopic grain faults in the structure of the sapphire. This, and Item 4, may cause a breach failure during vessel assembly or testing.
6. **Other problems** – The vessel wall thickness may have to be excessively thick to stand the high pressure and temperature occurring during the manufacturing processes. Also, the end cap bonding can create additional technical challenges.

These technical difficulties are not trivial and some of them may never be resolved. Furthermore, even if it were built overcoming all the difficulties, the sapphire cube could easily break and its inner surface might contaminate with sodium vapor sooner or later during the test. This means we may need tens of cubes costing $13k per piece.

Therefore, a modified idea is being considered to build a cube consisting of an alloy or ceramic “casket” covered with a sapphire flat top (Fig. 1).

[1] K. D. Kihm, D. M. Pratt, and A. D. Swanson, “Condensation of Sodium Vapor and High-Temperature Reaction with Quartz Pore Inner Surface,” *Journal of Heat Transfer-Photogallery*, Vol. 131, Issue 8, 080908-1, 2009.

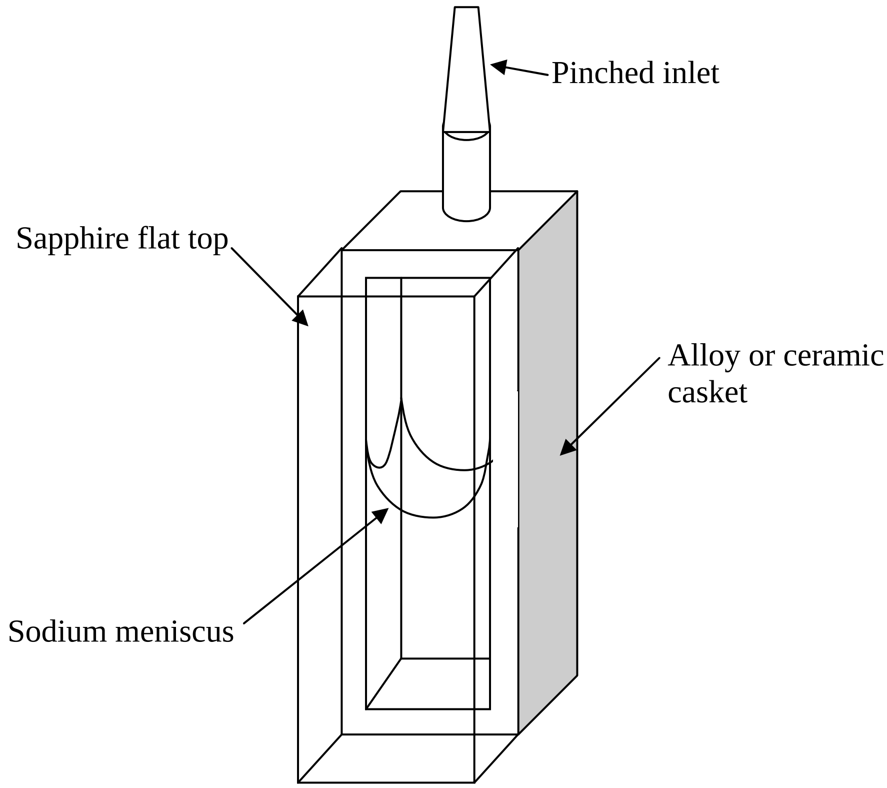


Fig. 1 Schematic of a sapphire-alloy (or ceramic) cube design

This new design is expected to alleviate almost all technical difficulties listed above. The cube will be more resisting to thermal and mechanical stresses as well. Another merit is that thermocouple probes can be easily placed or embedded along the casket wall as many as needed. Also, it will cost substantially less and the turn out time will be a lot shorter.

A couple of quick important points need to be not overlooked:

1. The sapphire cover and the casket will have to be bonded probably by brazing. The choice of casket material requires both inertness to sodium vapor and extremely low thermal strain to be compatible with sapphire.

2. The inner corners formed by the sapphire cover and the casket need to be maintained sharp and free from any residue materials that can be squeezed out from brazing.

1-b. Induction heating of meniscus

The electrical heater tape was found very difficult to provide stable, uniform and controllable heat flux to a capillary. It often ended up with overheating to cause sudden boiling.

For an electrically conducting medium like sodium, magnetically induced alternating current will activate the abundant free electrons inside to aggressively move and heat the medium as a result of Joule heating effect. The process will be far more controllable, repeatable, and quickly responsive with high efficiency (> 90%) in comparison with the electrical heater.

The induction heating technology is available for diverse applications; however, no one has tried to heat a liquid metal capillary to our knowledge. A proper configuration of the induction coil to fit for our purpose will be explored by contacting induction heater manufacturers.

1-c. Tomographic x-ray imaging of the liquid metal meniscus

The x-ray CT facility at WP Bdg. 653 can possibly image through a prototype heat pipe containing either lithium or sodium coolants. Some preliminary study has already been tried using a similar facility at Lockheed-Martin.

The shortcoming of x-ray imaging at Lockheed Martin was that it required high energy intensity to see through the metal wall and its frame rate was very slow that took 8 seconds to record each frame.

More information on the WP x-ray CT facility will be obtained including its frame rates and spatial resolution in the near future.

1-d. Neutron wave imaging of the liquid metal meniscus

Neutron wave imaging has an advantage of allowing high-speed frame rates because it requires relatively low energy intensity compared with x-ray imaging.

A 3” x 4” Haynes 188 sheet of 0.03” thick has been sent to Dr. Dan Hussey at NIST to examine the transmittance of the alloy that is being used to construct the prototype liquid metal heat pipes. His test showed 81% transmittance, which seemed promising for the feasibility of high-speed imaging of the heat pipe in operation.

From the safety concern, however, the neutron wave activates cobalt (39 weight % contained in Haynes 188) and tungsten (14 weight %) to emit their radiation waves. From the safety concern point, the relatively short half-life times of sodium (15 hrs) and tungsten (45 hrs) will make them acceptable for “being safe” after two weeks of sealed storage period.

The extremely long half-life of cobalt (272 days), however, is a problem because any material with significant amounts of Cobalt has to be indefinitely stored once exposed to neutron wave for imaging.

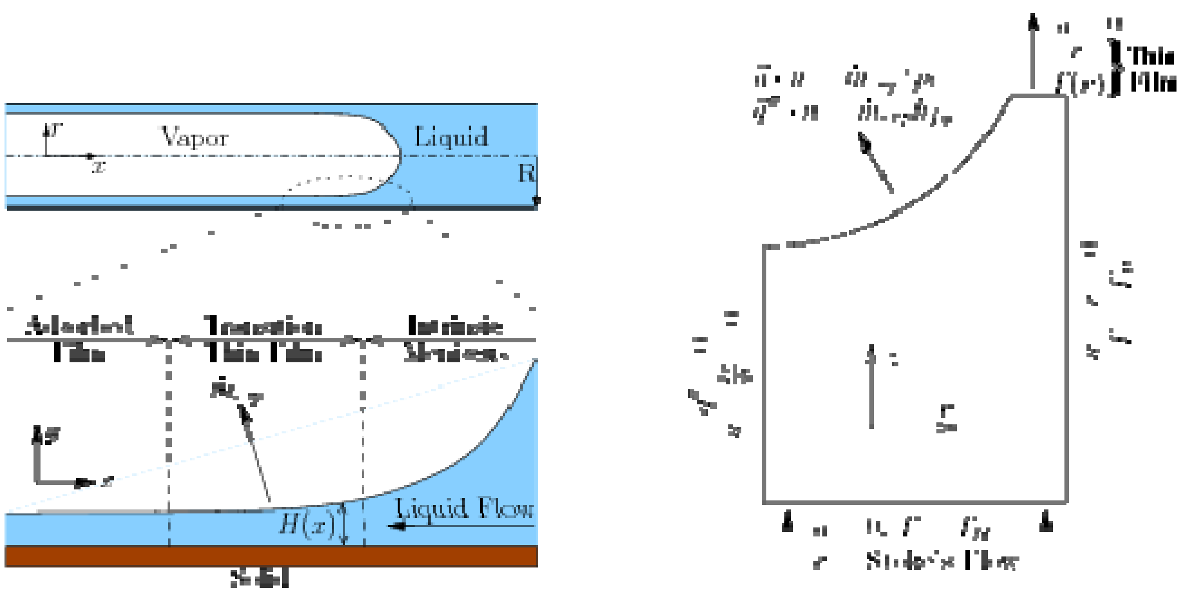
So, before going with any further consideration of neutron wave imaging, we need to know if it is possible to have a different heat pipe material, one with no or very little cobalt.

2. Multi-Scale Theoretical Characterization of Evaporating Sodium Capillary

A new multi-scale model of an evaporating liquid metal (Na) capillary meniscus has been developed with non-isothermal interface boundary conditions.

For the micro/nano-scale transition thin film (Fig. 2a), the unsimplified dispersion force will be modeled along with an electronic disjoining pressure component that is unique to liquid metals attributing to their abundant free electrons.[2] This thin film model will be coupled to a CFD model of the evaporating bulk meniscus considering the appropriate boundary conditions (Fig. 2b).

Integration of the evaporative mass flux across the total meniscus surface area will allow comparisons between total capillary evaporative mass flow rates between possible electronic disjoining pressure states. The results are expected to provide knowledge on the exclusive effect of the electronic component on the evaporation rate. Furthermore, the anticipated results will include the film thickness profiles and the evaporative mass flux distributions along the multi-scale capillary.



(a) (b)

Fig. 2 (a) Schematic of a cylindrical capillary geometry identifying the distinct regions of the multi-scale evaporating meniscus, and (b) a schematic of the bulk evaporating capillary meniscus CFD geometry and boundary conditions.

[2] J. B. Tipton, Jr., K. D. Kihm, and D. M. Pratt, , "Modeling Alkaline Liquid Metal (Na) Evaporating Thin Films Using Both Retarded Dispersion and Electronic Force Components," *Journal of Heat Transfer* (in press).

■ FUTURE DIRECTIONS

1. Upon Dr. Pratt's agreement, a new sapphire-alloy/ceramic cube will be designed and fabricated.

2. A customized induction heater will be designed and constructed.

3. Microscale optical imaging of evaporative liquid metal meniscus will be further exploited using the new cube with an induction heating device.

4. Both x-ray CT and neutron wave imaging will be continually examined to study macroscopic imaging of a prototype heat pipe.

5. Theoretical characterization of liquid metal thin film will be continued primarily at Dr. Kihm's laboratory at the University of Tennessee.

Appendix A

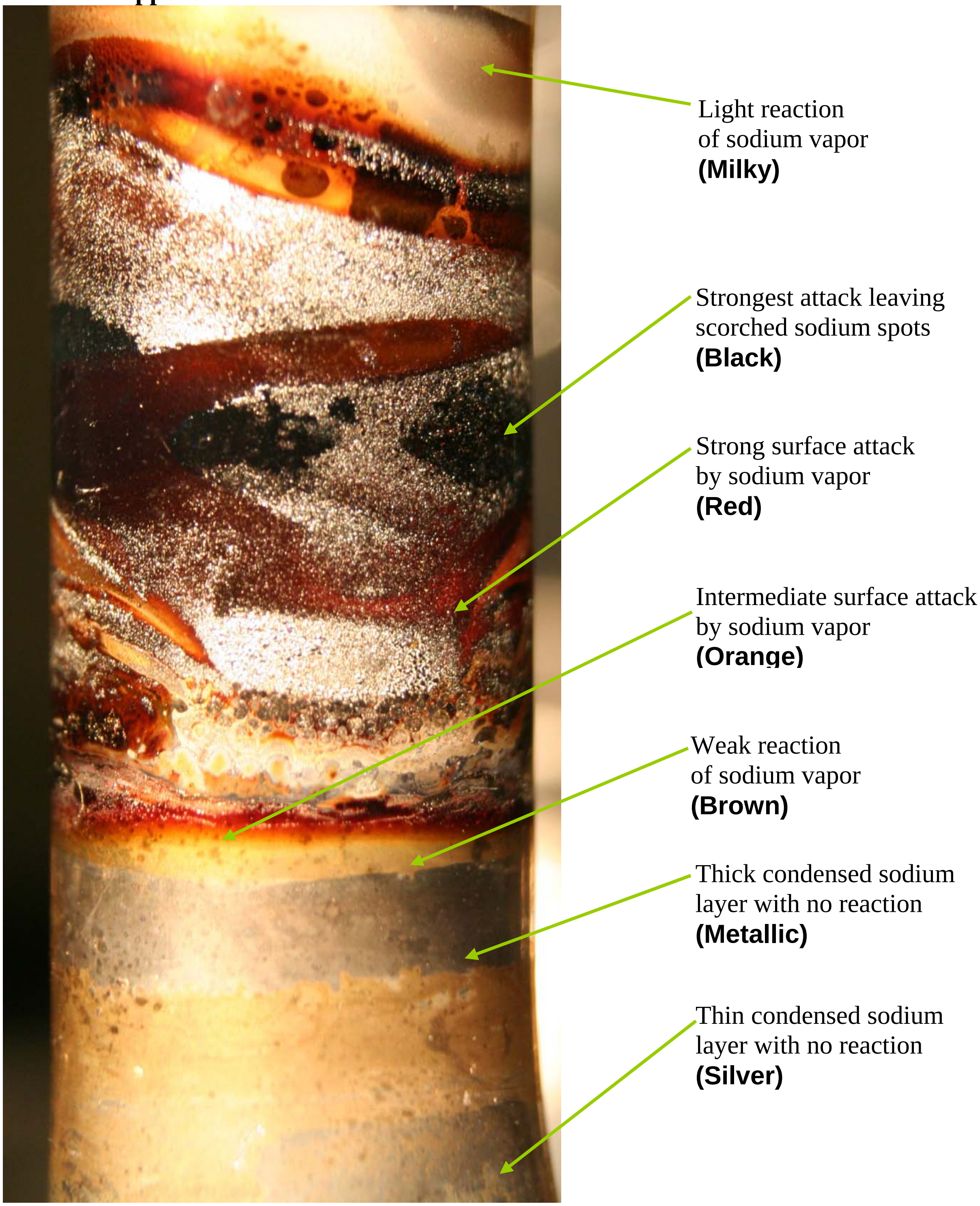


Fig. A-1 Condensation of high-temperature sodium vapor that has chemically/physically reacted with quartz pore inner surface. The condensation "fingerprints" express different color bands from silver, metallic, milky, brown, orange, red, and black with increasing level of the sodium attack and reaction on the surface.